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Solar and wind opportunities for water desalination in the Arab regions

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ABSTRACT

Despite the abundance of renewable energy resources in the Arab region, the use of solar thermal, solar photovoltaics, and wind is still in its technological and economic infancy. Great potential exists, but economic constraints have impeded more rapid growth for many applications. These technologies have certainly advanced technically over the last quarter century to the point where they should now be considered clean-energy alternatives to fossil fuels. For the Arab countries and many other regions of the world, potable water is becoming as critical a commodity as electricity. As renewable energy technologies advance and environmental concerns rise, these technologies are becoming more interesting partners for powering water desalination projects. We evaluate the current potential and viability of solar and wind, emphasizing the strict mandate for accurate, reliable site-specific resource data. Water desalination can be achieved through either thermal energy (using phase-change processes) or electricity (driving membrane processes), and these sources are best matched to the particular desalination technology. Desalination using solar thermal can be accomplished by multistage flash distillation, multi-effect distillation, vapor compression, freeze separation, and solar still methods. Concentrating solar power offers the best match to large-scale plants that require both high-temperature fluids and electricity. Solar and wind electricity can be effective energy sources for reverse osmosis, electrodialysis, and ultra- and nano-filtration. All these water desalination processes have special operational and high energy requirements that put additional requisites on the use of solar and wind to power these applications. We summarize the characteristics of the various desalination technologies. The effective match of solar thermal, solar photovoltaics, and wind to each of these is discussed in detail. An economic analysis is provided that incorporates energy consumption, water production levels, and environmental benefits in its model. Finally, the expected evolution of the renewable technologies over the near- to mid-term is discussed with the implications for desalination applications over these timeframes.

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1. Introduction

Desalination is a water-treatment process that separates salts from saline water to produce potable water or water that is low in total dissolved solids (TDS). Worldwide to date, more than 15,000 industrial-scale desalination units had been installed or contracted, and they account for a total capacity of more than 8.5 billion gallons/day [1].

Desalination techniques are mainly classified into two types: (1) processes based on physical change in the state of the water or distillate through evaporation, and (2) processes using a membrane that employ the concept of filtration. Based on installed capacity, the leader in the market place is the membrane desalination process of reverse osmosis (RO), with 44% of total capacity; this is followed closely by the thermal process of multi-stage flash (MSF), with 40% of total capacity. The remaining 16% is divided between other thermal processes, such as multiple-effect desalination (MED) with 4% and vapor compression (VC) with 3%, and membrane processes, such as electrodialysis (ED) with 6%, and other newer-concept systems with 3% [2].

The main sources of feed water for desalination are seawater (58%), brackish ground water (23%), and other sources such as rivers and small salt lakes [2]. The cost of obtaining potable water by using desalination processes has decreased substantially—and at a consistently rapid annual rate throughout recent decades. Over the past 50 years, the per unit cost of MSF, which is a distillation desalination technology that has been used in some form for centuries, has decreased by an average of 44% per decade. In addition, the increasing cost of conventional water supplies due to overexploitation and scarcity has aided desalination in becoming one of the top options for boosting potable water supply.

This paper provides insight into various aspects of desalination and how renewable energy resources can be coupled to desalination systems. A brief outline of the technical side of the main desalination processes is followed by an assessment of their respective advantages and disadvantages. The paper then delineates a general economic assessment of the conventional and solar-coupled desalination processes. This includes a range of cost estimates of competing processes as stated in the literature and how they compare to alternative sources of water supply.

2. Main desalination technologies

The main desalination processes are divided into the following two types of processes (Fig. 1) and other alternative processes [3].

2.1. Distillation processes

Distillation processes mimic the natural water cycle as saline water is heated, producing water vapor, which in turn is condensed to form fresh water. These processes include: multi-stage flash distillation (MSF), multi-effect distillation (MED), and vapor-compression distillation (VC). Forty percent of the world's desalination capacity is based on the MSF desalination principle. However, other distillation technologies, such as MED and VC distillation, are rapidly expanding and are anticipated to have a more important role in the future as they become better understood and more accepted. These processes require thermal or mechanical energy to cause water evaporation. As a result, they tend to have operating cost advantages when low-cost thermal energy is available [3].

2.1.1. Multi-stage flash distillation

In MSF, seawater feed is pressurized and heated to the plant's maximum allowable temperature. When the heated liquid is discharged into a chamber maintained at slightly below the saturation vapor pressure of the water, a fraction of its water content flashes into steam. The flashed steam is stripped of suspended brine droplets as is passes through a mist eliminator and condenses on the exterior surface of the heat-transfer tubing. The condensed liquid drips into trays as hot fresh-water product. Fig. 2 is a diagram of a typical MSF unit.

2.1.2. Multi-effect distillation

MED units operate on the principle of reducing the ambient pressure at each successive stage, allowing the feed water to undergo multiple boiling without having to supply additional heat after the first stage. In this unit, steam and/or vapor from a boiler or some other available heat source is fed into a series of tubes, where it condenses and heats the surface of the tubes and acts as a heat-transfer surface to evaporate saline water on the other side. The energy used for evaporation of the saline water is the heat of condensation of the steam in the tube. The evaporated saline water—now free of a percentage of its salinity and slightly cooler—is fed into the next, lower-pressure stage where it condenses to fresh-water product, while giving up its heat to evaporate a portion of the remaining seawater feed. Fig. 3 is a diagram of an MED unit.

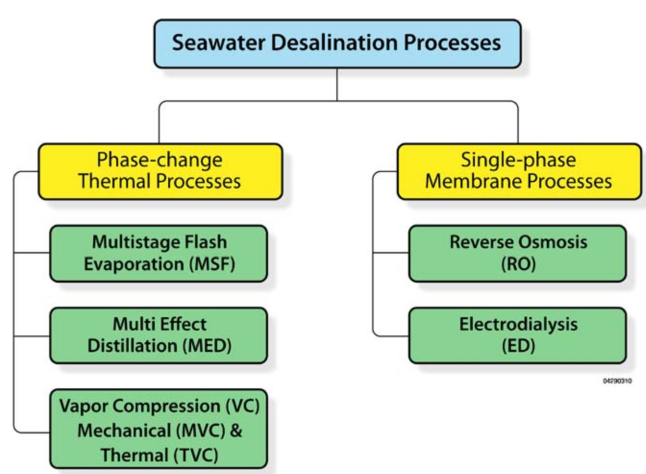


Fig. 1. Main desalination processes.

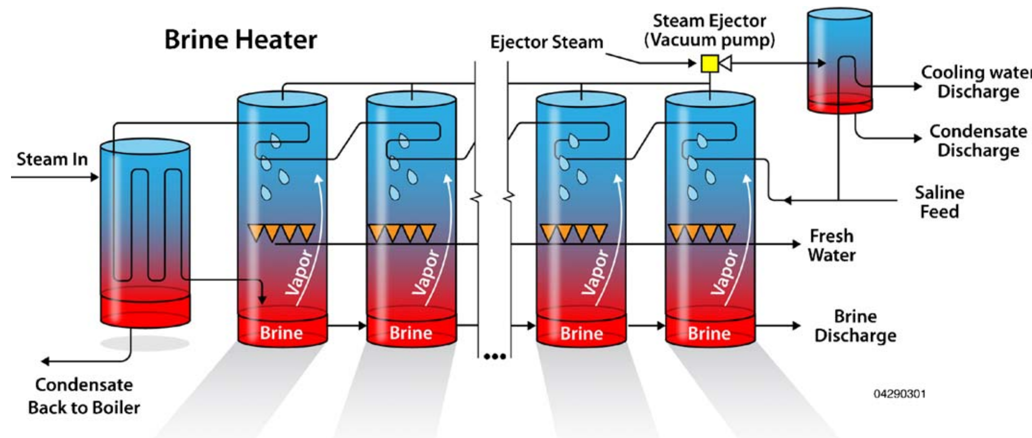


Fig. 2. Diagram of a multi-stage flash distillation (MSF) unit.

2.1.3. Vapor-compression distillation

The VC distillation process is generally used for small- and medium-scale seawater desalting units. The heat for evaporating the water comes from the compression of vapor, rather than from the direct exchange of heat from steam produced in a boiler. The plants that use this process are generally designed to take advantage of the principle of reducing the boiling-point temperature by reducing the pressure. Two primary methods are used to condense vapor so as to produce enough heat to evaporate incoming seawater: a mechanical compressor or a steam jet. The mechanical compressor (MVC) is usually electrically driven, allowing the sole use of electrical power to produce water by distillation (Fig. 4a).

With the steam jet-type of VC unit, also called a thermo compressor (TVC), a Venturi orifice at the steam jet creates and extracts water vapor from the main vessel by creating a lower ambient pressure in the main vessel. The extracted water vapor is compressed by the steam jet. This mixture is condensed on the tube walls to provide the thermal energy (heat of condensation) to evaporate the seawater being applied on the other side of the tube walls in the vessel (Fig. 4b).

VC units are usually built in the range of 20–2000 cum/d (0.005–0.5 mgd), and they are often used for resorts, industries, or other sites where fresh water is not readily available.

2.2. Membrane processes

In nature, membranes play an important role in the separation of salts, as in the processes of dialysis and osmosis occurring in the human body. Membranes are used in two commercially important desalination processes: reverse osmosis and electrodialysis. Each process uses the ability of membranes to differentially and selectively separate salts and water. However, membranes are used differently in each of these processes [3].

2.2.1. Reverse osmosis

In reverse osmosis (RO), water in a pressurized saline solution is separated from the solutes (i.e., the dissolved material) by a membrane. No heating or phase change is necessary for this separation, and the major energy requirement is for pressurizing the feed water. In practice, the saline feed water is pumped into a closed vessel, where it is pressurized against the membrane (Fig. 5). As a portion of the water passes through the membrane, the salt content of the remaining feed water increases because there is less water containing the same total amount of dissolved salts. At the same time, a portion of this saltier feed water is discharged without passing through the membrane. RO units have a waste discharge of brackish water or brine that can range from 35% to 100% of its output of fresh water, depending on the feed

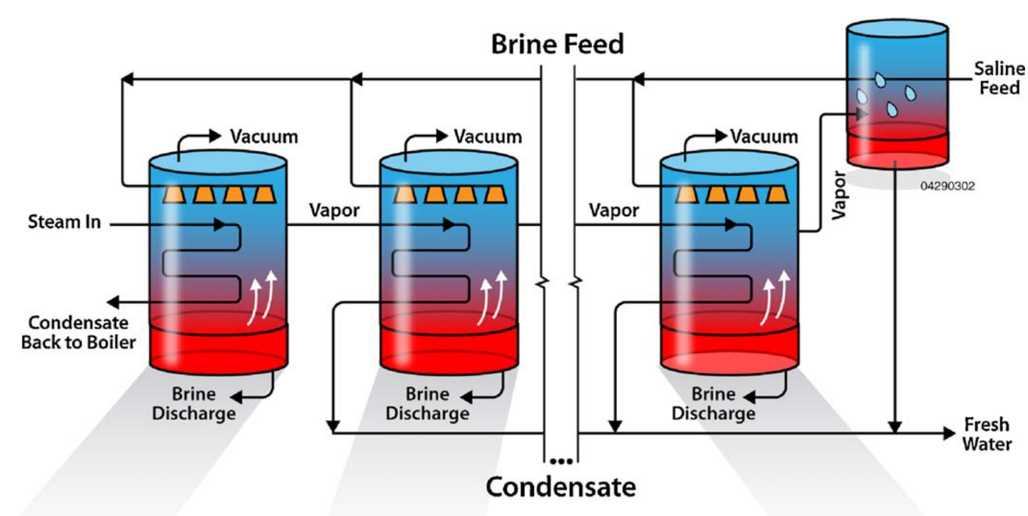


Fig. 3. Diagram of a multi-effect desalination (MED) unit.

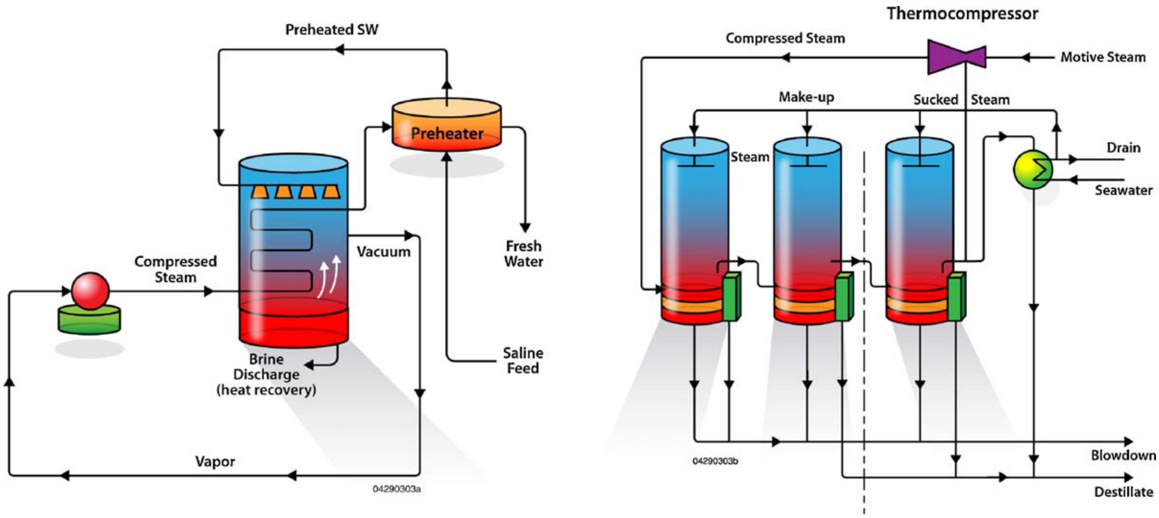


Fig. 4. (a) Diagram of a mechanical vapor compression (MCV) and (b) diagram of a thermal vapor compression (TVC).

water being treated. During the past decade, two improvements have helped reduce the operating costs of RO plants—the developments of membranes that can operate efficiently at lower pressures, and the use of energy recovery devices. Low-pressure membranes are being widely used to desalinate brackish water because they save on the energy costs associated with pumping.

2.2.2. Electrodialysis

The basic electrodialysis (ED) unit consists of several hundred cell pairs bound together with electrodes on the outside and referred to as a membrane stack. Feed water passes simultaneously through the cells to provide a continuous, parallel flow of desalted product water and brine that emerge from the stack (Fig. 6). The ED process is only economical when used on brackish water, and it tends to be most economical at TDS levels of up to 4000–5000 mg/L.

In the early 1970s, an American company commercially introduced the EDR process for electrodialysis. An EDR unit operates on the same general principle as a standard electrodialysis plant except that both the product and the brine channels are identical in construction. At intervals of several times an hour, the polarity of the electrodes is reversed, and the flows are simultaneously switched so that the brine channel becomes the product-water channel, and the product-water channel becomes the brine channel. The result is that the ions are attracted in the opposite direction across the membrane stack. Immediately following the reversal of polarity and flow, enough of the product water is dumped until the stack and lines are flushed out, and the desired water quality is restored. This flush takes about 1 or 2 min, and the unit can then resume producing water. The reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells before they can build up and create a problem. Flushing allows the unit to operate with fewer pretreatment chemicals and minimizes membrane fouling.

3. Desalination with renewable energy systems

Using desalination technologies driven by renewable energy sources (RES) is a viable way to produce fresh water in many locations today. As the technologies continue to improve—and as fresh water and cheap conventional sources of energy become scarcer—RES desalination will become even more attractive. Fortuitously, renewable energy (RE) has unique synergies in regions where desalination is most needed. Fig. 7 shows the possible combination of solar and wind systems with desalination process.

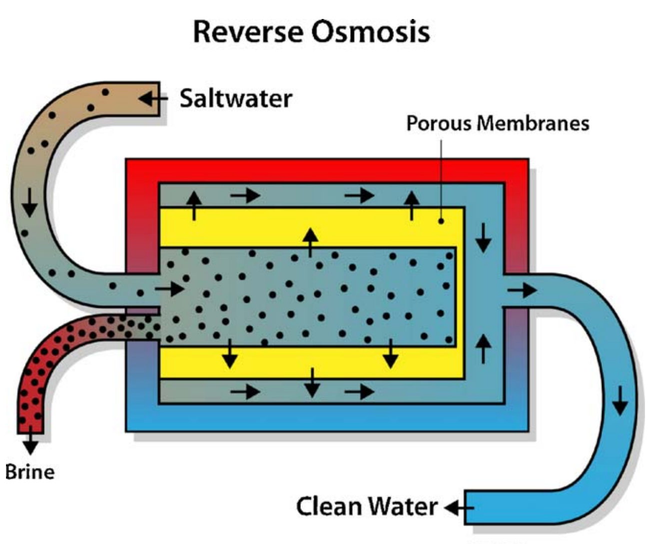


Fig. 5. Diagram of a reverse-osmosis desalination (RO) process.

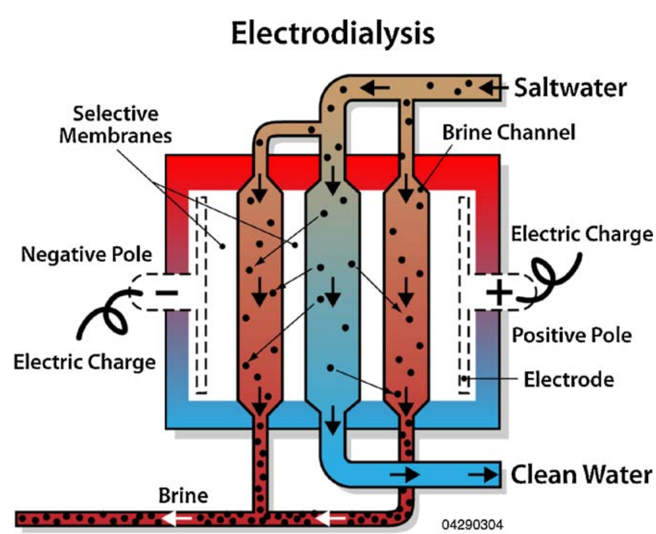


Fig. 6. Movement of ions in the electrodialysis (ED) process.

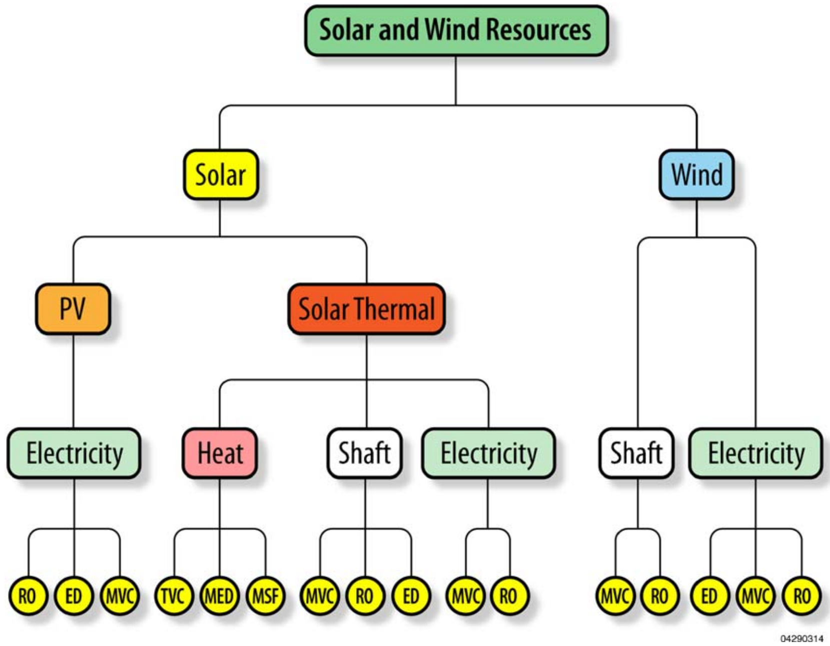


Fig. 7. Possible combination of solar and wind systems with desalination processes.

Proper matching of standalone power-supply desalination systems has been recognized as being crucial if the system is to provide a satisfactory supply of power and water at a reasonable cost. Selecting the appropriate RES desalination technology depends on a number of factors, including the following: amount of water needed (plant size), feed-water salinity, remoteness, availability of grid electricity, technical infrastructure, and the type and potential of the local RE resource. In particular, RES/desalination systems are currently promising for remote regions, where connection to the public electrical grid is either not cost effective or feasible, and where water scarcity is severe. Standalone systems for electricity supply in isolated locations are now proven technologies. Table 1 presents the most promising combinations of solar and wind resources with desalination technologies.

Especially during the last two decades, numerous desalination systems using RE have been constructed. Most of these plants have been research or demonstration projects with small capacity. Several of these plants no longer exist; most are pilot units, and after the project ends, there is no interest or budget to continue operations.

3.1. Solar thermal desalination systems

Two types of systems could be included in this category: (1) Simple solar operated devices such as solar stills; (2) solar assisted distillation systems such as multi-effect humidification systems. These devices have low efficiency and low water productivity due to the ineffectiveness of solar collectors to convert most of the energy they capture, and to the intermittent availability of solar radiation.

Table 1
Most promising combination of desalination processes with RES.

RE resource	Desalination process				
	MSF	MED	VC	RO	ED
Wind			√	√	
Solar photovoltaic				√	√
Solar thermal	√	√			

For this reason, solar thermal desalination has so far been limited to small-capacity units, which are appropriate in serving small communities in remote areas, exposed to water scarcity and at the same time, are characterized by high levels of solar radiation.

3.1.1. Solar still

Solar-still designs can generally be grouped into four categories: (1) basin still, (2) tilted-wick solar still, (3) multiple-tray tilted still, and (4) concentrating mirror still. The basin still consists of a basin, support structure, transparent glazing, and distillate trough. Thermal insulation is usually provided underneath the basin to minimize heat loss. Other ancillary components include sealants, piping and valves, storage, external cover, and a reflector (mirror) to concentrate light. Single basin stills have low efficiency, generally below 45%, due to high top losses. Double glazing can potentially reduce heat losses, but it also reduces the transmitted portion of the solar radiation [4].

A tilted-wick solar still uses capillary action of fibers to distribute feed water over the entire surface of the wick in a thin layer. This allows a higher temperature to form on this thin layer. Insulation in the back of wick is essential. A cloth wick needs frequent cleaning to remove sediment built-up and regular replacement of wick material due to weathering and ultraviolet degradation. Uneven wetting of the wick can result in dry spots that reduce efficiency.

In a multiple-tray tilted still, a series of shallow horizontal black trays are enclosed in an insulated container with a transparent glazing on top. The feed-water supply tank is located above the still, and the vapor condenses and flows down to the collection channel and finally to the storage. The construction of this still is fairly complicated and involves many components that are more expensive than simple basin stills. Therefore, the slightly better efficiency it delivers may not justify its adoption.

The concentrating mirror solar still uses a parabolic mirror for focusing sunlight onto an evaporator vessel. The water is evaporated in this vessel exposed to extremely high temperature. This type of still entails high construction and maintenance costs.

Solar stills are characterized by low production rates of about 4–6 L/(m^2 day). Three types of solar stills are shown in Fig. 8.

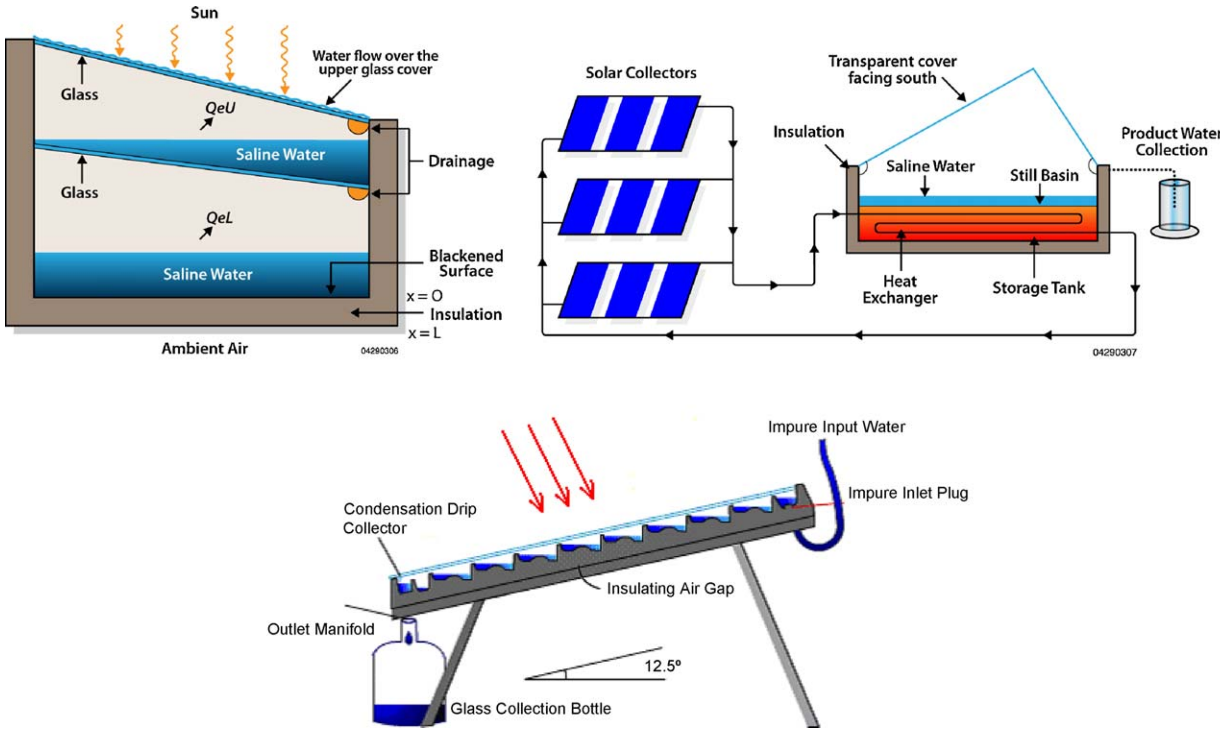


Fig. 8. Schematic diagrams of a simple solar still.

3.1.2. Multi-effect humidification

Multi-effect humidification (MEH) is based on the distillation process that occurs under atmospheric conditions by an air loop saturated with water vapor. MEH falls into two types of processes: (1) open-water/closed-air cycle, and (2) open-air/closed-water cycle.

In the first type of MEH unit, air circulates between a humidifier and a condenser using natural or forced-draft circulation. Saline water feed is preheated in the condenser by the latent heat condensation of water that would have been lost in a single-basin still. The feed water leaving the condenser section is further heated in the solar collector before being sprayed over packing in the humidifier section.

In the second type of MEH unit, the water heats and humidifies the cold mixed air entering the evaporator. The warm, moist air then enters the condensing section and heats the saline water feed before it is discharged from the system. The water is circulated in the system, as shown in Fig. 9.

According to Bourouni et al. [5], the MEH principle offers several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity, and the possibility of using low-temperature energy such as solar energy. MEH units are very compact, consisting of an evaporator where air is humidified and a condenser where distilled water is recovered. The energy requirements in an MEH process are for compensation of sensible heat loss of salt water, pumping salt water, and blowing the air.

3.2. Desalination systems driven by solar thermal

The solar thermal part of the distillation plant includes a field of solar collectors, where a thermal fluid is heated. The collectors must be able to heat the thermal fluid to medium temperatures so that after appropriate heat transfer, the water fed to the evaporator reaches temperatures between 70 and 120 °C.

The best-known solar thermal distillation combination is solar multi-effect (MED) distillation. From an energy perspective, the main supply to the desalination plant is a large thermal input, as well as some auxiliary electricity required for pumping.

In a theoretical study carried out by Sagie et al. [6] using selective coating evacuated tube solar collectors coupled to an MED process. They showed that a combination of a large number of effects of evaporation and high-pressure saturated steam available for recycling yields a dramatic improvement in the production rate of water desalination with a modest increase in the desalination installation cost. In their study they presented the fresh water production cost based on electricity cost of \$0.065 kWh^{-1} for three levels of desalination capacity: (1) fresh water cost of \$1.2 m^{-3} for a small 1000 m^3/day plant typical for serving small settlements or industries at rural locations, isolated from fresh water and grid power sources; (2) fresh water cost of \$0.92 m^{-3} for a medium size plant of 10,000 m^3/day typical for serving a city; (3) fresh water cost of \$0.69 m^{-3} plant on the scale of a national water supply plant. The study also indicated that when electricity cost is above \$0.071 kWh^{-1}, the solar-MED plant is more economical than RO plant. Fig. 10 shows a combination of solar thermal-MED plant diagram.

In general, thermal distillation systems are unstable in small sizes. This leads to the use of medium- and large-size evaporators that do no quite fit with the sizes and capacities usually applied with renewable energies—unless a huge solar field can be built, which, in turn, implies large ground areas. Therefore, the combination of solar-thermal/distillation seems best suited for medium and high production capacities. However, research has also been done in small capacities. Table 2 presents several existing solar thermal MED plants.

3.3. Desalination systems driven by wind

Wind turbines can be used to supply electricity or mechanical power to desalination plants. Few applications have been implemented using wind energy to drive a mechanical vapor compression unit. A pilot plant was installed in 1991 at Borkum, an island in Germany, where a wind turbine with a nominal power of 45 kW was coupled to a 48 m^3/day MVC evaporator. A 36-kW compressor was required. The experience was followed in 1995 by another larger plant at the island of Rügen. Additionally, a 50 m^3/

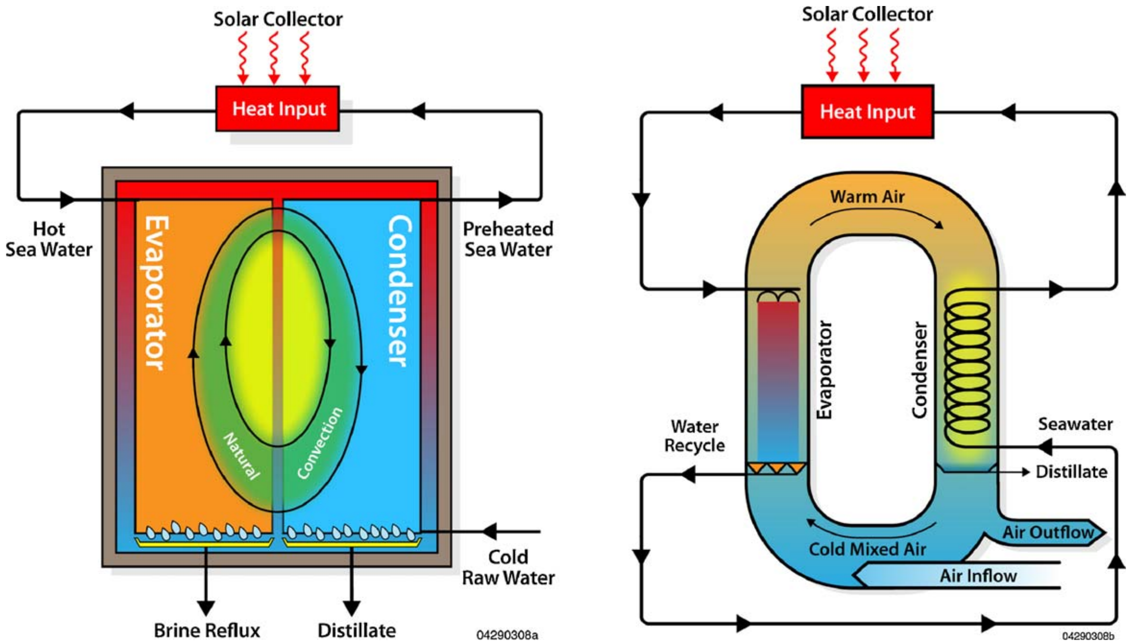


Fig. 9. Schematic diagram of a MEH unit: (a) with an open-water/closed-water cycle; (b) with an open-air/closed-water cycle.

day wind MVC plant was installed in 1999 by the Instituto Tecnologico de Canarias (ITC) in Gran Canaria, Spain, within the Sea Desalination Autonomous Wind Energy System (SDAWES) project [7]. The wind farm is composed of two 230-kW wind turbines, a 1500-rpm flywheel coupled to a 100-kVA synchronous machine, an isolation transformer located in a specific building, and a 7.5-kW uninterruptible power supply located in the control dome. One of the innovations of the SDAWES project, which differentiates it from other projects, is that the wind generation system behaves like a mini power station capable of generating a grid similar to conventional ones without the need to use diesel sets or batteries to store the energy generated.

Regarding wind energy and RO combinations, a number of units have been designed and tested. As early as 1982, a small system

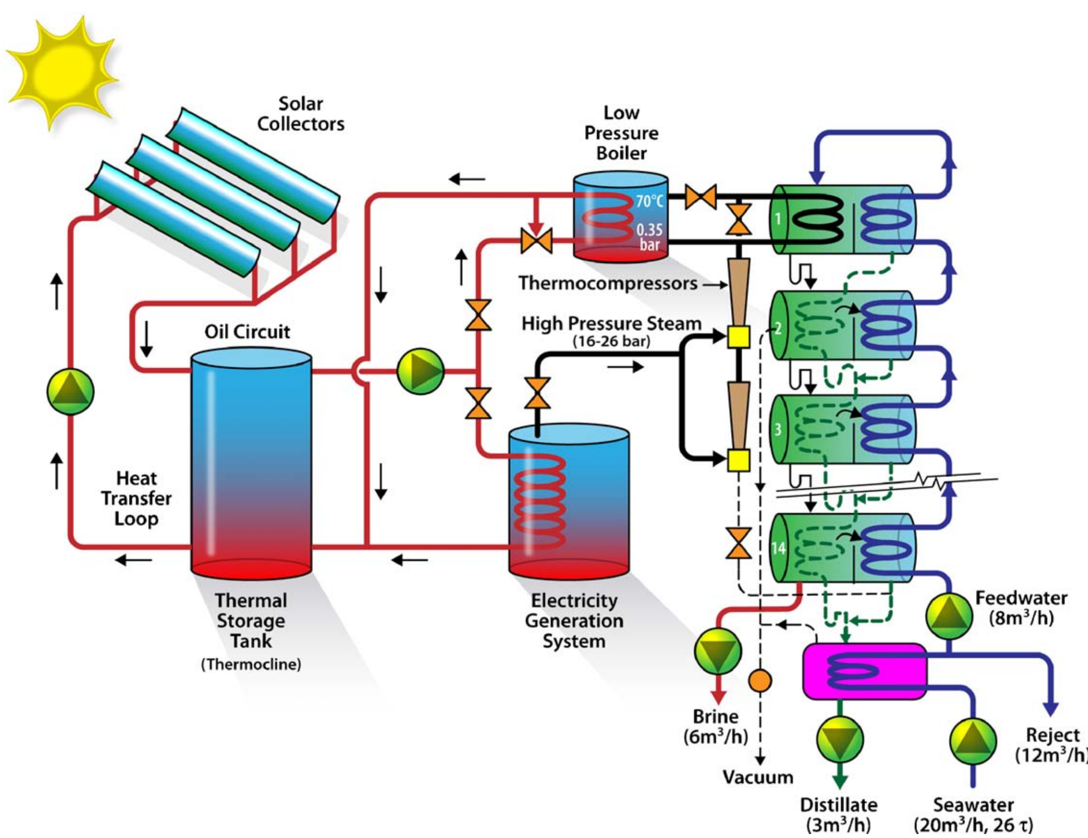


Fig. 10. A combination of solar thermal-MED plant diagram.

Table 2
Solar thermal distillation plants.

Plant location	Year of commission	Water type	Capacity (L/h)	RES installed power	Unit water cost ($/m^3)
Almeria, Spain, CIEMAT	1993	SW	3000	2.672 m^2 solar collector area	3.6–4.35
Hazeg, Sfax, Tunisia	1988	BW	40–50	80 m^2 solar collector area	25.3
Pozo Izquierdo, Gran Canaria, SODESA Project	2000	SW	25	50 m^2 solar collector area	–
Sultanate of Oman, MEDRC Project	2002	SW	42	5.34 m^2 solar collector area	–

SW: seawater; BW: brackish water.

was set at Ile du Planier, France [8], which as a 4-kW turbine coupled to a 0.5-m^3/h RO desalination unit. The system was designed to operate via either a direct coupling or batteries.

Another case where wind energy and RO was combined is that of the Island of Drenec, France, in 1990 [9]. The wind turbine, rated at 10 kW, was used to drive a seawater RO unit. A very interesting experience was gained at a test facility in Lastours, France, where a 5-kW wind turbine provides energy to a number of batteries (1500 Ah, 24 V) and via an inverter to an RO unit with a nominal power of 1.8 kW.

A 500 L/h seawater RO unit driven by a 2.5-kW wind generator (W/G) without batteries was developed and tested by the Centre for Renewable Energy Systems Technology (CREST) UK. The system operates at variable flow, enabling it to make efficient use of the naturally varying wind resource, without need of batteries [10].

Excellent work on wind/RO systems has been done by ITC within several projects such as AERODESA, SDAWES, and AEROGEDESA [2].

Additionally, a wind/RO system without energy storage was developed and tested within the JOULE Program (OPRODES-JOR-CT98-0274) in 2001 by the University of Las Palmas. The RO unit has a capacity of 43–113 m^3/h, and the W/G has a nominal power of 30 kW [11].

In addition, a great job on the combination of wind/RO has been done by ENERCON, the German wind turbine manufacturer. ENERCON provides modular and energy-efficient RO desalination systems driven by wind turbines (grid-connected or standalone systems) for brackish and seawater desalination. Market-available desalination units from ENERCON range from 175 to 1400 m^3/day for seawater desalination and 350 to 2800 m^3/day for brackish-water desalination. These units in combination with other system components, such as synchronous machines, flywheels, batteries, and diesel generators, supply and store energy and water precisely according to demand [12]. Table 3 shows several existing wind/RO installations.

3.4. Desalination systems driven by solar photovoltaics

The main advantages of the coupling of photovoltaics (PV) with desalination units are the following: ability to develop small desalination plants, limited maintenance cost of PV, and ease of transportation and installation. RO usually uses AC for the pumps, which means that DC/AC inverters are required. Energy storage is again a matter of concern, and batteries are used for PV output power smoothing or for sustaining system operation when solar energy is insufficient. The main disadvantage of this coupling is the high cost of PV. The typical PV/RO applications are standalone [13]. Several installed PV/RO systems are presented in Table 4.

Solar Energy Systems (SES) in Australia is commercializing a small PV/RO unit, developed at Murdoch University, capable of producing about 400 L/day of water from feed water containing up to 5000 ppm TDS. They have installed about 20 systems, primarily in three desert areas of Australia. The system is designed for 15–20% water recovery. Part of the reason for the low water recovery is to reduce problems with scaling. One of the problems that SES encountered was biological fouling of pre-filters during field-testing in Western Australia and Indonesia. Also, failures of plunger pumps (manufactured in-house by SES) have been reported; the design was changed to correct this problem.

Table 3
Installed wind/RO plants.

Plant location	Year of commission	Water type	Capacity (L/h)	W/T nominal power (kW)	Unit water cost ($/m^3)
Ile de Planier, France	1983	SW/BW	500	4	–
Fuerteventura island, PUNTA JANDIA Project	1995	SW	2333	225	–
Therasia island, Greece	1997	SW	200	15	–
Pozo Izquierdo, Gran Canaria, AEROGEDESA Project	2003	SW	800	15	4.4–7.3
CREST, UK	2004	SW	500	2.5	2.6

Table 4
Several PV/RO installed plants.

Location	Feed water (ppm)	Capacity (m^3/day)	PV (kWp)	Batteries (kWh)	Energy consumption (kWh/m^3)	Water cost ($/m^3)	Year
Sadous, S. Arabia	5800	15	10.08	264			1994
Elhamarawien, Egypt	3500	53	19.8 + 0.64 control	36	0.89	11.6	1986
Heelafar Rahab, Oman	1000	5	3.25	9.6		6.25	1995
Hassi-Kheba Algeria	3200	0.95	2.59	Non		10	
Inetl, Portugal	5000	0.1–0.5	0.05–0.15	Non			2000
White Cliffs, Australia	3500	0.5	0.34	Non	2–8		
Coite-Pedreias, Brazil	BW	0.25	1.1	9.6	3–4.7	14.9	2000
Mesquite, Nevada	3500	1.5	0.4		1.38	3.6	2003
Conception,Mexico	3000	0.71	2.5	Non	6.9		1982
Lampedusa, Italy	SW	40	100	880	5.5	9.5	1990
St. Luci, FL	SW	0.64	2.7		13		1995
ITC Canaries Island, Spain	SW	3	4.8	19	5.5	13	1998

Table 5
Installed hybrid RO plants.

Plant location	Year of commission	Water type	Capacity (L/h)	RES nominal power	Unit water cost ($/m^3)
Maagan Michel	1997	BW	125–375	3.5 kWp PV, 0.6 kW W/G, 3 kW diesel	~11.6
AUA, Athens	2001	SW	62–125	850 Wp PV, 1 kW W/G	–
Lavrio, Attiki, Greece	2001	SW	130–150	3.9 kWp PV, 0.9 kW W/G	33.55

3.5. Hybrid desalination systems

Autonomous hybrid systems are independent and incorporate more than one power source. One important application is the use of PV and wind generators to drive RO desalination units. Diesel generators are mainly used as backup; however, fuel transportation to remote areas poses the same difficulties as water transportation [14]. Table 5 presents three installed hybrid RO plants.

4. Economic aspects

We now look at the economic aspects of desalination, first from a general perspective, then focusing on an analysis of renewable energy desalination processes.

4.1. General economic assessment of desalination

The economies of desalination and the decision as to which approach to select are contingent on situation-specific parameters. Because energy is the main driver in the cost of operation, economic feasibility of either approach to desalination is highly correlated to the location specific-cost and availability of energy [15]. Table 6 present a comparative illustration of energy's share of total operational cost for a 10 mgbd seawater RO plant and 10 mgbd MSF plant installed in Libya.

In the representative example above, the capital cost is considerably higher for the thermal than for the membrane process. This reflects the prevailing situation in the desalination industry, in which the construction cost of thermal desalination plants, exceeds that of membrane plants. All other main costs related to operating a desalination plant are usually higher for membrane processes due to the greater complexity of maintenance tasks and operation. Accordingly, cost of chemicals is 7% vs. 2%, maintenance and parts are 14% vs. 7%, and labor cost is 9% vs. 7% of total operating cost for the representative RO and MSF plants, respectively. Membrane replacement, which is listed separately, adds further to the maintenance cost for RO, whereas this cost is obviously absent for thermal processes.

Strong inter-firm competition and advances in technology have resulted in average annual unit cost reductions of close to 6% for MSF processes since 1970. In addition, many MSF desalination plants, which are mostly located in the Middle East, have increasingly taken advantage of economies of scale. RO, which has been used commercially only since 1982, has seen even steeper cost declines since inception. Membrane costs have fallen by 86% between 1990 and 2002 [13]. Steeply declining maintenance cost, in combination with relatively low capital cost, has contributed much to the rapidly growing success of membrane technology.

The unit product cost of fresh water differs when it is produced from different plant capacities. Table 7 shows the unit product cost of water produced from plants of different type and capacity. Product unit prices generally take into account all relevant costs originating from direct capital, indirect capital, and annual operating costs.

Table 6
Percentage of cost for conventional systems.

Type of plant	Capital cost	Energy cost	Maintenance and repair cost	Membrane replacement	Labor	Chemicals
RO	31%	26%	14%	13%	9%	7%
MSF	42%	41%	8%	0%	7%	2%

4.2. Economic analysis for re desalination processes

Technical feasibility of renewable-powered desalination systems should be accompanied by economic feasibility to justify the implementation of the technology. Despite the free nature of renewable energy resources, their collecting systems are not always viable or affordable. Therefore, it is important to look at the economic aspects of desalination systems powered by various renewable energy sources.

Because of limited commercialization of solar units, the capital costs and operating costs are not as well established as for the other processes. For solar stills, the cost of water production is high due to the low productivity of these stills. However, this type of desalination is only used in remote areas where there is no access to conventional energy resources [16]. Table 8 compares the water costs for simple and multi-effect solar stills. As shown, the water costs for multi-effect solar stills are much lower than for simple stills.

For the hybrid plants (distillation and RE system), we can assume that the capital costs of the solar generating system will significantly exceed that of the desalination unit. The economics of operating solar desalting units tend to be related to the cost of producing energy with these alternative energy devices. At this time, the cost tends to be high, but may be expected to decline as further development of these devices reduces their capital cost. The capital cost of an 80 m^3/day solar-assisted MED facility installed at Umm Al Nar in Abu Dhabi was recently estimated at about $2 million, or about $25,000/(m^3 day) of installed capacity

Table 7
Fresh water cost for different types and capacities.

Type of system and capacity (mgbd)	Product cost ($ Cent/gallon)
MVC (0.03)	1.894
MVC (0.13)	1.220
MVC (1.06)	0.939
MVC (1.20)	0.920
MVC (5.28)	0.174
MSF (7.13-dual purpose)	0.292
MSF (7.13-single purpose)	0.621
MSF (gas turbine, waste heat boiler)	0.545
MSF (9.99)	0.473
MED (6-dual purpose)	0.330
MED (6-single purpose)	0.739
MED (9.99)	0.409
MED (gas turbine, waste boiler)	0.496
RO (5.28, single stage)	0.242
RO (5.28, two stage)	0.288
RO (0.03)	0.898
RO (1.06)	0.750
RO (1.20)	0.489
RO (9.99)	0.413
RO (30)	0.208
MED-TVC (single purpose)	0.866
MED-TVC (dual purpose)	0.496

Table 8
Water costs for simple and multi-effect solar stills [16].

Type	Capacity/productivity	Water cost ($/m^3)	Description	Reference
Solar stills	4 L/(m^2 day)	23.80	20 years lifetime, collector cost: $315 m^{-2}, 5% interest rate	Tembiltz-Sembitsky [17]
Multi-effect stills	12 L/(m^2 day)	9.95	Storage module, 20 years lifetime, 5% interest rate	Tembiltz-Sembitsky [17]
Multi-effect stills	20 L/(m^2 day)	<9.0[a]	Non-corroding polymer absorbers, storage, 24-h operation	Tembiltz-Sembitsky [17]

[a] Predicted.

Table 9
Distribution of costs for conventional (RO and MF) desalination systems and for systems driven by RE [16].

Type of process	Capital costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22–27	14–15	59–63
Conventional (MSF)	25–30	38–40	33–35
Renewable	30–90	10–30	0–10

Table 10
Cost comparison of solar pond-powered desalination with conventional SWRO.

System type	Capacity (m^3/day)					
	SWRO		SP-MED		SP-HYB	
	20,000	200,000	20,000	200,000	20,000	200,000
Investment (mil. $)	20.0	160.0	48.0	380.0	32.0	250.0
Specific investment ($/(m^3 day))	1000	800	2400	1900	1600	1250
Unit water cost ($/m^3)	0.77	0.66	0.89	0.71	0.79	0.65

[18]. Table 9 shows the comparison of cost distribution for conventional systems (RO and MSF) and plants driven by an RE system. For the renewable systems, the investment costs are the highest and the energy costs are the lowest.

In a 1995 study, Glueckstern showed that solar-pond desalting systems have considerable potential to be cost effective if favorable site conditions exist [16]. Table 10 presents the cost comparison of solar-pond-powered desalination with conventional seawater reverse osmosis (SWRO) for two production capacities (20,000 and 200,000 m^3/day). As seen from the table, the unit water cost difference is relatively small. However, investment costs and specific investment cost for solar-powered systems are still higher compared with the SWRO systems, where the difference decreases as the capacity increases.

Suri et al. [19] studied the techno-economic viability of solar desalination using PV and low-grade thermal energy using solar ponds. They compared the cost of water production of a conventional cogeneration system (producing electricity and water) and that of solar-powered MSF and RO systems. The figures in Table 11 were based on a plant capacity of 1 m^3/day and annual utilization factors of 75% for solar-based systems and 90% for conventional systems.

Table 11
Cost of water production using conventional and solar-powered MSF and RO systems.

Parameter	Conventional system	Partial solar-based system	Complete solar-based system
MSF			
Annual water production (m^3)	328	274	274
Cost of water production ($/m^3)	1.75	1.79	2.84
RO			
Annual water production (m^3)	328	274	274
Cost of water production ($/m^3)	1.30	5.70	12.05

As shown, the cost of water production of a conventional RO system is less than that of a conventional MSF system. However, for solar-based systems, the partial solar-based MSF system gives the lowest cost of water production.

5. Conclusions

Desalination technology, developed extensively over the past 40 years, is now reliably used to produce fresh water from saline sources. This has effectively made possible the use of saline waters for water resource development. The costs for desalination can be significant because of its intensive use of energy. However, in many arid areas of the world, the cost to desalinate saline water is less than other alternatives that may exist or be considered for the future. Desalinated water is used as a main source of municipal water supply in many areas of the Caribbean, North Africa, and the Middle East. Using desalination technologies, especially for softening mildly brackish water, is increasing rapidly in various parts of the world.

There is no "best" method of desalination. Generally, distillation and RO are used for seawater desalting, whereas RO and electrodialysis are used to desalt brackish water. However, the selection of a process should depend on a careful study of site conditions and the application at hand. Local circumstances may play a significant role in determining the most appropriate process for an area.

The renewable/conventional hybrid systems such as solar/MSF, solar/MED, and solar-wind/RO have mainly been investigated theoretically. These studies have indicated that these systems could compete with conventional systems under certain circumstances. Very few solar desalination plants have been reported in the literature. The economic competitiveness of solar/MED and solar/MSF technologies with systems using conventional sources has been shown in a number of theoretical studies. However, this has not been verified experimentally and therefore cannot be used as a guide for decision-making regarding technology selection for a particular application.

Solar-powered desalination technologies are suitable and may be the only technically and economically competitive alternative for small desalination capacities up to 10 m^3/day to provide drinking water in remote areas where access to fuel, electricity, and technical expertise is not available.

The economic analyses carried out so far have not been able to provide a strong basis for comparing economic viability of each desalination technology. The economic performances expressed in terms of cost of water production have been based on different system capacity, system energy source, system component, and water source. These differences make it difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others.

Areas of current and future research on solar thermal desalination focus on the following three aspects: (1) enhancing solar-energy collection, (2) improving the technology of desalination techniques, and (3) better matching the solar field and desalination unit. These areas of investigation directly relate to the economic performance improvement of the system.

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